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THE ROLE OF RADIATION IN THE SURFACE FLUX BUDGET OF THE NOCTURNAL BOUNDARY LAYER: A QUESTION OF TIMESCALE

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1. INTRODUCTION

The role of longwave (LW) radiation in the surface flux budget of the nocturnal boundary layer (NBL) is not well understood. As the surface cools, the upward flux from the surface is reduced, but since a significant fraction of the downward LW flux reaching the surface may originate from within the NBL itself, the downward flux also decreases, so that the reduction in the net LW flux is smaller than that in the upward LW flux. This reduces the effectiveness of LW radiation in arresting the cooling of the surface, a phenomenon sometimes referred to as runaway cooling.

The common understanding of the role of radiation in the surface flux budget of the NBL is heavily indebted to Brunt (1932), who proposes a simple formula for the downward radiative flux at the surface,

$$LW^{\downarrow} = \sigma T_a^4 (a + b\sqrt{e}_a), \tag{1}$$

where T_a and e_a are the near-surface air temperature and water vapour pressure and a and b are constants. The net upward LW flux is therefore approximately $R_N = \sigma T_a^4(1-a-b\sqrt{e}_a)$. Brunt comments (p. 406) that, "The vapour pressure has only a slight diurnal variation, and since the fall of temperature during the night is only a relatively small fraction of $T_{[a]}$, we may assume as a first approximation that R_N is constant." He then derives an expression for the change in the surface temperature, ΔT_s, in the case where R_N is constant and the sensible heat flux, H is 0:

$$\Delta T_s = -\frac{2}{\sqrt{\pi}} \frac{R_N}{\sqrt{k_s \rho_s c_s}} \sqrt{t}, \tag{2}$$

where t is the time and k_s, ρ_s and c_s are respectively the thermal conductivity, density and specific heat capacity of the soil. Whilst this formula often proves reasonably accurate for mid-latitude NBLs on clear calm nights, it predicts an unrealistically large fall in T_s over snow. Consequently, either H must be significant over snow or R_N must decrease. In fact, direct calculation of T_s using a numerical model with a full radiation code (eg. Edwards, 2009a,b) shows that after a short period of rapid cooling T_s enters a phase wherein it cools much more slowly than implied by the above formula, even if $H = 0$.

Nevertheless, in boundary layer research more emphasis has been placed on the possibility that H may be significant in the very stable boundary layer than on the possibility that R_N may decrease. Indeed, Betts (2006) remarks that "Surprisingly, comparatively little attention has been paid to the corresponding role of radiative forcing in determining the strength and depth of the NBL..." Betts (2004, 2006) introduces a radiative temperature scale, $R_{N24}/(4\sigma T^3)$, where R_{N24} is the net LW flux over a 24-hour period and shows how this may be used to scale the diurnal range of temperature. (Subsequently, a temperature scale related to that suggested by Betts will be introduced.)

The GABLS3 intercomparison of single column models (Bosveld et al. 2014, BLM, to appear) again raises the equation of radiation's role in the surface flux budget of the NBL. Bosveld et al. 2014 seek to quantify the impact of different parameterizations of turbulence, surface characteristics and radiation on the simulation of a mid-latitude NBL under clear skies and, as a common reference, introduce an extension of Brunt's formula for $LW^{\downarrow}$ that takes some account of the temperature profile of the NBL by including conditions at 2 and 200 m,

$$\begin{aligned} LW^{\downarrow} &= (a + b\sqrt{e_{200}})\sigma T_2^4 \\ &+ (c + d\sqrt{e_{200}})\sigma (T_{200}^4 - T_2^4) \\ &+ f, \end{aligned} \tag{3}$$

where T_2 and T_{200} are the temperatures at 2 and 200 m, e_{200} is the vapour pressure at 200 m and $a, \ldots, f$ are constants derived for typical mid-latitude boundary layers. This predicts that R_N is 30% more sensitive to changes in T_s than does Brunt's formula.

These considerations suggest that there might be value in developing a simple conceptual model that provides some quantitative understanding of when changes in R_N play a significant role in determining the evolution of the NBL. We therefore consider the downward longwave radiative flux at the surface

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and its response to surface cooling, introducing the concept of a radiative efficiency, which is then used to define a time scale for the net radiative flux to adjust to surface cooling. On this basis, it is suggested that it is not so much that LW radiation is incapable of arresting the cooling of the surface, but rather that in some cases the relevant radiative time scale is large in relation to other time scales of the system and therefore that the potential effect of LW radiation can be masked.

2. THE NET RADIATIVE FLUX AT THE SURFACE

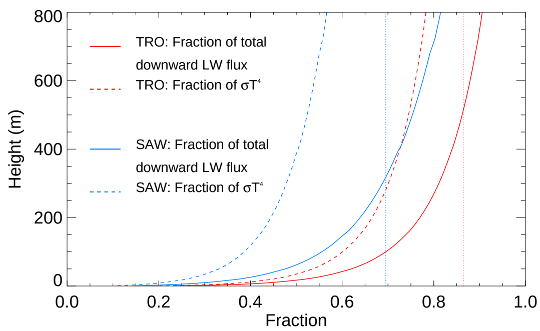

Figure 1: The downward flux at the surface emitted from below a given height in the atmosphere, expressed as a fraction of the total downward flux emitted by the whole atmosphere (solid) and as a fraction of the upward flux from the surface (dashed). Thin vertical lines represent the ratio of total downward flux to upward flux. Curves are shown for a tropical atmosphere in red and for a sub-arctic winter atmosphere in blue.

Assuming that the surface emissivity is unity, the upward radiative flux from a surface at a temperature T_s is σT_s^4. The downward flux depends on the concentrations of radiatively active gases in the atmosphere, principally water vapour and carbon dioxide, and emission from all layers contributes to the surface flux, so that the actual value of the flux depends on the entire temperature profile. Because atmospheric transmission varies greatly with wavelength and the atmosphere is relatively opaque to terrestrial radiation, except for wavelengths between 8 and 12 μm (the atmospheric window) the downward flux at the surface is strongly affected by conditions in the lowest few tens of metres of the atmosphere.

As the surface cools, the emitted upward flux is reduced, thus reducing the net flux; but cooling of the lower atmosphere simultaneously reduces the downward flux, thus mitigating the reduction of the net flux. The transmission of the atmosphere over the depth of the boundary layer is therefore an important quantity in understanding cahnges in the surface flux budget. Following the climatological calculations of Ohmura (2001), Bosveld et al. (2014) calculate that, in the case of GABLS3, 50% of the radiation comprising the downward flux at the surface originates from the lowest 100 m of the atmosphere. Figure 1 shows the ratio of the component of the downward flux at the surface originating below a certain level in the atmosphere to the total downward flux for a tropical and a sub-arctic winter atmosphere. Notice the very steep increase in this ratio close to the surface. The ratio is also shown relative to the upward flux from the surface, since it is the difference between the upward and downward fluxes that determines the surface cooling. In the tropical atmosphere, the ratio of the net flux to the upward flux, $R_N/(\sigma T_s^4)$, is 0.16, while in the sub-arctic winter atmosphere it is 0.30.

By linearizing the response of the net radiative flux to changes in the surface temperature, we are led to define a radiative efficiency as

$$\eta = \frac{dR_N}{d(\sigma T_s^4)}, \tag{4}$$

so that

$$\Delta R_N = \eta \frac{d(\sigma T_s^4)}{dT_s} \Delta T_s. \tag{5}$$

η is a measure of how much the net flux is reduced in response to a reduction of the upward flux due to a reduction in T_s. If the downward flux were unaltered upon a reduction in T_s, η would be 1; while if the reduction in the downward flux exactly equalled that in the upward flux, so that the net flux was unaltered, η would be 0. It is important to note that since the downward flux at the surface is only indirectly and not completely determined by the surface temperature, this quantity does not fully describe the radiative response of the boundary layer. Rather, it should be regarded as a conceptual simplification providing some insight into the radiative response to surface cooling.

η depends on the depth and shape of the boundary layer and it is now calculated for a range of self-similar boundary layers with temperature profiles of the form

$$\Delta T = \Delta T_s f(z/h), \tag{6}$$

where h is the depth of the boundary layer and f is

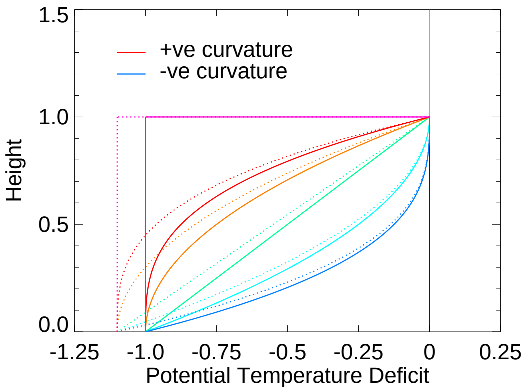

Figure 2: Normalized profiles of potential temperature before (solid) and after (dashed) an incremental surface cooling. Colours indicate different degrees of curvature, with negative curvature in blues, neutral curvature in green and positive curvature in orange, red and magenta.

a prescribed function of the form

$$f(\zeta) = \begin{cases} 1-\zeta^n & n \geq 1 \text{ for positive curvature} \\ (1-\zeta)^n & n \geq 1 \text{ for negative curvature.} \end{cases} \tag{7}$$

Figure 2 shows these normalized shapes and the effect of a cooling increment, from which η may be calculated. A distinction is often made between NBLs with positive curvature, which are typically associated with higher levels of turbulence, and NBLs with negative curvature that are more typical of weak turbulence (André, 1981). The magenta lines show the case of extreme positive curvature, where the cooling is uniform throughout the boundary layer. Such uniform cooling also occurs in the case of a quasi-equilibrium boundary layer of a constant depth (cf. Nieuwstadt, 1984).

Figure 3 shows the radiative efficiency as a function of boundary layer depth, h, for different degrees of curvature, with the colours matching those in figure 2 in tropical and sub-arctic winter atmospheres. As the boundary layer depth is increased, the efficiency decreases. Efficiencies are higher in the case of negative curvature and in the sub-arctic case. In general terms, these effects are determined by the ratio of the photon mean free path (appropriately weighted by frequency) to h.

The broken grey lines show the ratio of the net to the upward flux, $R_N/\sigma T_s^4$. These values lie much below the calculated efficiencies for the deepest boundary layers, even in the case of positive curvature. If

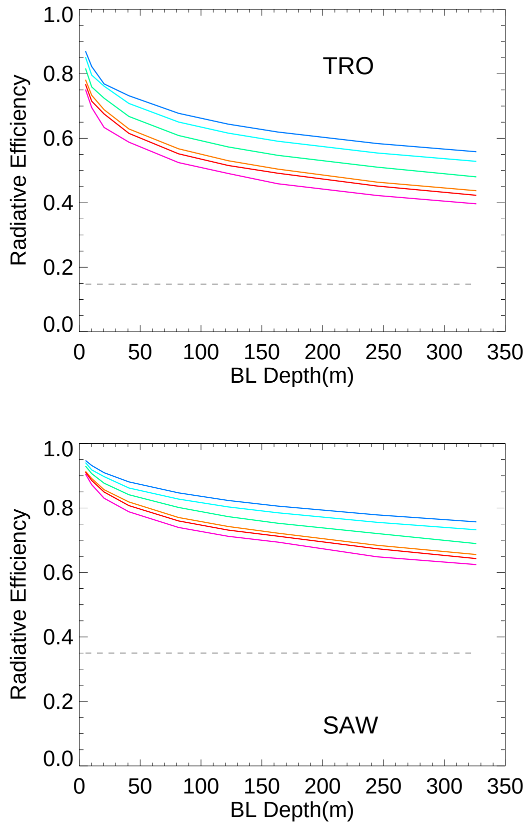

Figure 3: Radiative efficiencies as a function of boundary layer depth in a tropical (top) and a sub-arctic winter atmosphere (bottom) for different degrees of curvature as indicated by colours corresponding to the idealized shapes shown in 2. Grey lines show the ratio $R_N/\sigma T_s^4$.

the downward radiation is calculated from a formula of the type introduced by Brunt (1932), where the temperature dependence of the downward flux is represented solely by T_s^4, η will attain this value. We may conclude that formulae of this type will underestimate the effectiveness of radiation in reducing R_N, since they are equivalent to assuming a uniform cooling throughout the entire depth of the atmosphere.

3. AN IDEALIZED MODEL OF SURFACE COOLING

We now consider an idealized model of surface cooling. We suppose that the ground is initially at a temperature, T_0, and that the net radiative flux is R_{N0}. Linearizing the change in R_N in response to changes in T_s,

$$R_N = R_{N0} + \eta\Lambda\Delta T_s, \qquad (8)$$

where $\Lambda = 4\sigma T_0^3$, a temperature scale, $R_{N0}/(\eta\Lambda)$, may be defined (cf. Betts 2004, 2006). Denoting by z the depth in the soil, the surface boundary condition on the fluxes becomes

$$k_s \frac{\partial T_s}{\partial z} = R_{N0} + \eta\Lambda\Delta T_s. \qquad (9)$$

Since a temperature scale has already been defined, this equation implies a length scale, $\mathcal{L} = k_s/(\eta\Lambda)$. Within the soil, the evolution of the temperature is governed by the diffusion equation,

$$\frac{\partial T}{\partial t} = \kappa_s \frac{\partial^2 T}{\partial z^2}, \qquad (10)$$

so, from the length scale, a time scale, $\mathcal{T} = (k_s/(\eta\Lambda)^2)/\kappa_s$ may be defined.

Non-dimensionalizing the change in the soil temperature, $\Delta T = T(z) - T_0$, the depth, z, and the time, t, with the appropriate scales, the evolution of the soil temperature is governed by the system of equations

$$\frac{\partial \Delta T}{\partial t} = \frac{\partial^2 \Delta T}{\partial z^2} \qquad (11)$$

$$\Delta T = 0 \quad \text{at } t = 0\text{, and} \qquad (12)$$

$$\frac{\partial T}{\partial t} = 1 + \Delta T \quad \text{at } z = 0. \qquad (13)$$

This system may be solved by taking a Laplace transform, giving an equation for the change in the surface temperature as

$$\Delta T_s = -1 + \frac{2}{\pi} \int_0^\infty \frac{e^{-tu^2}}{1+u^2} du. \qquad (14)$$

An analytical expression for this integral may be obtained as

$$\Delta T_s = -1 + e^t(1 - \text{erf}(\sqrt{t})). \qquad (15)$$

However, an approximate solution provides more immediate insight into the nature of the solution. Setting $e^{-tu^2} \approx 1/(1+tu^2)$ in 14, we obtain,

$$\Delta T_s = \frac{-\sqrt{t}}{1+\sqrt{t}}, \qquad (16)$$

which underestimates the magnitude of the cooling by no more than 13%. It indicates that the surface temperature initially decreases proportionally to $\sqrt{t}$, as in Brunt's analytic solution, but that the rate of cooling becomes much slower once the non-dimensional time exceeds 1.

Returning to dimensional units, this implies that the reduction in R_N plays a significant role in arresting the decrease of T_s at times longer than the time scale

$$\mathcal{T} = \frac{\rho_s c_s k_s}{\eta^2 \Lambda^2}. \qquad (17)$$

If the lifetime of the NBL is shorter than this, changes in R_N will play only a limited role in reducing the rate of cooling of the surface. Substituting typical values of the surface properties taken from Garratt (1992), we obtain estimtes of η for some illustrative cases.

1. A deep tropical NBL over a moist clay soil: $\mathcal{T} \approx$ 10d.
2. A subtropical NBL with low humidity over dry sand: $\mathcal{T} \approx$ 7h.
3. A shallow polar SBL over fresh snow: $\mathcal{T} \approx$ 1h.

4. DISCUSSION

A simple idealized model to present some insight into the role of LW radiation in the surface flux budget of the NBL has been presented. A radiative time scale that involves both the surface characteristics and a radiative efficiency arises naturally from the model. This time scale is inversely proportional to the square of the efficiency. LW radiation is expected to play a significant role in arresting the reduction of the surface temperature when this time scale is shorter than the lifetime of the NBL. The radiative efficiency has been calculated for some illustrative boundary layer profiles and been shown to be higher than the efficiency that would be obtained from simple formulae for the downward flux at the surface that involve only a surface or near-surface air temperature. However, the limitations of this model should be borne in mind. Even in a single NBL, the evolution is not exactly self-similar, nor does the height remain constant, so the efficiency will vary as the NBL evolves. Deepening of the NBL while T_s changes only slightly will result in a reduction in the downward flux, while the upward flux is almost unchanged, giving large negative values of η, so it is a less useful concept in such cases.

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